



Challenges to color constancy in a contemporary light

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Color constancy is a prime example of a perceptual constancy, giving stability to mental representations of objects in an unstable world. Yet color constancy is highly variable, depending on the illumination, the object and its context, and the viewer. Color constancy is particularly challenged by artificial lights that differ from the natural illuminations under which human vision evolved. The rapid developments in solid-state lighting technologies revive the need to scrutinise the limits of color constancy, to understand whether and how it is optimised for natural illuminations, and, in turn, to optimise novel lighting technologies for human color perception. For these goals, a deeper collaboration between the disciplines of human vision science and color science is needed.

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Introduction

There has long been a disjunction between physics-based color science and biology-based vision science in the approach to studying color, exemplified by the phenomenon of color constancy. In vision science, color constancy is a prime example of a perceptual constancy. Color constancy keeps the mental representation of object color stable despite changes in the retinal image due to changes in the light reflected from objects, in turn due to changes in

the illumination spectrum [1]. Its presumed behavioural purpose is to enable people to use object color as a robust and reliable cue for recognising and interacting with objects, based on their invariant surface spectral reflectance properties [2].

In color science, the term color constancy is scarcely used. Instead, it is expressly acknowledged that surface color appearance depends on the illumination. Two types of quantitative models exist to predict color appearance, both extensively used in industrial applications. Color appearance models, or CAMs [3*,4,5], predict the appearance of a stimulus specified by its retinal receptor responses (or specifically, its standard observer tristimulus values [6]) and the adapting illumination. A chromatic adaptation transform (CAT) normalises the stimulus receptor responses by the responses to a spectrally neutral surface (one which reflects light equally at all visible wavelengths) under the adapting illumination.

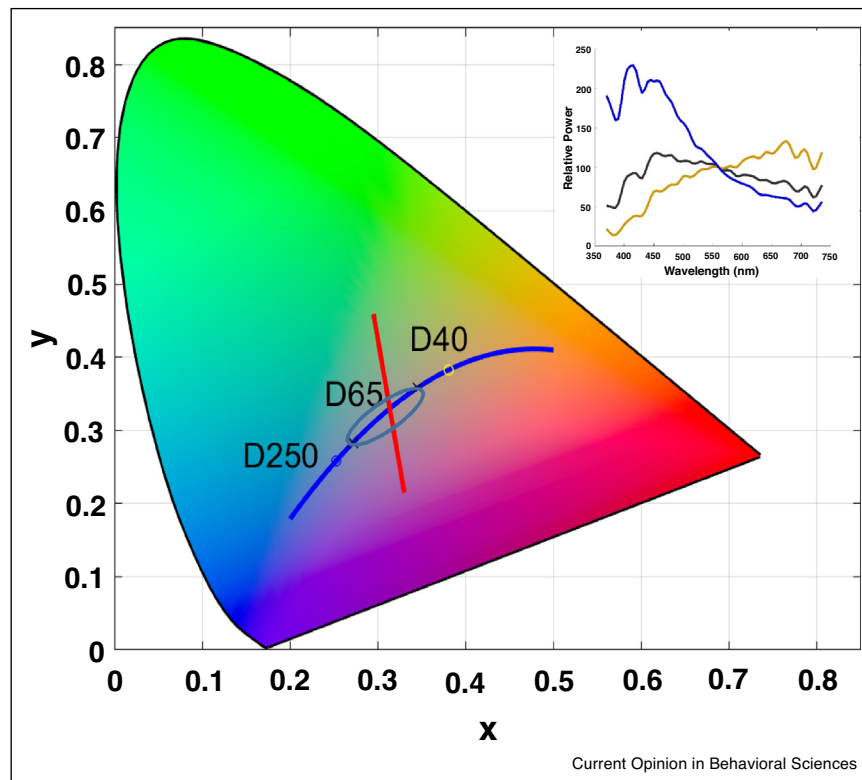
Color rendering models, or CRMs, apply to lights. CRMs characterise an illumination by its effects on the color appearances of a representative set of surfaces, relative to a reference illumination.¹ The reference illumination is a precisely defined broad-band spectrum, close to or on the daylight locus (the chromaticities of daylight, which vary from blue to yellow, closely following the Planckian curve; see [Figure 1](#)). Effectively, CRMs describe how well a particular illumination reproduces the color appearance of surfaces under daylight with the most similar chromaticity. (See [Figure 2](#) for an example of a CRM metric, the TM-30-18 [7]). CRMs assume complete adaptation to the tested illumination, and thus the best possible constancy (or fidelity) with respect to the most similar daylight ([Table 1](#)). Yet, even so, CRM fidelity indices vary widely across illumination spectra, demonstrating that constancy of color appearance rarely reaches even its best possible limit [7].²

In vision science, despite the pre-eminence of the phenomenon, color constancy is also acknowledged as neither

¹ CRMs depend on CAMs. TM-30-18 indices use the CAM02-UCS color space [4] rather than the updated CAM16-UCS [5], which calculates coordinates corresponding to lightness, redness–greenness, and yellowness–blueness, and from these, values for hue, brightness, chroma, colorfulness and saturation. The TM-30-18 characterises illuminations by an average color fidelity index (R_f), a gamut area measure (R_g), 48 other hue-specific measures of illumination-dependent appearance changes, and one summary graphic (see [Figure 2](#)). R_f describes the similarity, in terms of metric distance, between the perceptual color coordinates of representative surfaces under the test illumination and a reference illumination. The reference illumination is specified as a broad-band illumination of the same correlated color temperature (CCT) (either Planckian radiation, CIE daylight, or a specified mixture of the two, depending on the CCT), that is with the chromaticity of the nearest point on the daylight locus. It is also worth noting that CAMs, and therefore CRMs, undergo continual refinement, utilising different color spaces, and also may be modified to incorporate individual differences in receptor sensitivities.

² This variation in color fidelity between illuminations is largely because the chromatic adaptation transform cannot capture the nonlinear changes in cone responses induced by illumination changes on surfaces, especially those with highly chromatic, or highly variable, reflectance functions.

Figure 1



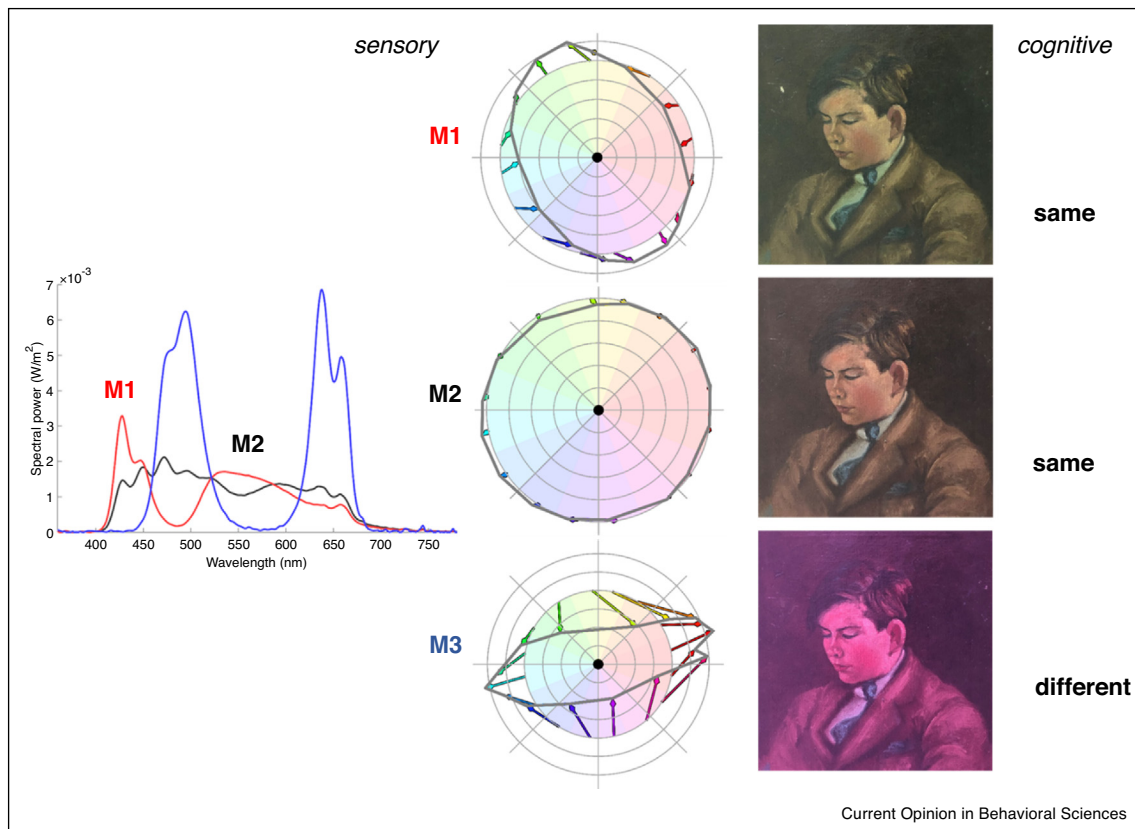
CIE chromaticity diagram. Blue line: daylight locus, with indicated locations of daylight of CCTs 4000 (D40), 6500 (D65), and 25000 (D250) K. Red line: locus of chromaticities orthogonal (in a perceptually uniform chromaticity plane) to the daylight locus at D65. Grey ellipse: Rough size and orientation of variability in perceptual whitepoints in a dark surround, redrawn from Bosten *et al.* [48]. Inset: Daylight spectra of 4000 K (orange), 6500 K (black), and 25 000 K (blue).

all or none. Estimates of the biological attainability of constancy range from the depressing – because of the metamerism built into a trichromatic system [8^{••},9] (see below) – to the optimistic – empirical measurements of color constancy performance, as tabulated in Ref. [10], show an increasing trend from 1986 to 2010 [11]. Yet there is another important distinction between the two fields. In color science, constancy (or rather, the lack thereof) is measured at the appearance level, where surfaces are matched in their colorimetric properties only (e.g. hue, saturation and brightness). In vision science, this corresponds to the ‘sensory’ level, appropriate for a chromatic adaptation transform that acts directly on retinal responses. But it is acknowledged that color constancy is achieved by multiple mechanisms acting on multiple levels, from retina to higher cortical areas. Accordingly, constancy is also measured at different levels: not only the sensory level (e.g. the ‘hue/saturation’ match in Ref. [12]), but also the ‘cognitive’ level, where people assess surface identity, regardless of changes in color appearance (e.g. the ‘paper’ match in Ref. [12]). Using distinct instructions on distinct tasks, Radonjić and Brainard [13] found that color constancy is indeed higher on the cognitive level than

the sensory level, and, specifically, highest for an object selection task. Similarly, color constancy as measured by assessing color category identity across illumination changes, is generally high [14,15] and higher than at the color appearance level [16].

It is also increasingly recognised in vision science that color constancy, however it is defined or measured, varies considerably between individuals. #thedress – the viral internet phenomenon of 2015, in which people argued over the color of a dress in a single photograph – brought home this inter-individual variability [17,18]. Differences in individuals’ underlying color constancy explain their differences in color naming: those who infer the illumination to be dim and bluish name the dress as white and gold, whereas those who infer the illumination as bright and yellowish name it blue and black [19–25]. Yet this ambiguity between illumination and surface reflectance seems peculiar to the distribution of chromaticities in the image, which closely parallel the daylight locus: rotating the distribution in the chromaticity plane so that it aligns with a red/green axis destroys the polymorphism [26,27]. The phenomenon therefore provides additional impetus

Figure 2



Effects of metameric illuminations on colour appearance. Left panel: Spectral power distributions of 3 illuminations (M1, M2 and M3), metameric to daylight of 6500 K, generated by tuneable multi-channel LED lamps. Middle left panel: Summary TM-30-18 colour distortion graphics for the corresponding metameric illuminations. Colour distortion vectors are plotted in the perceptually uniform CIECAM02 colour appearance space, and represent the average difference in appearance of a standard set of 99 surfaces, collected into 16 hue bins, between the test illumination and a broad-band reference illumination (Planckian radiation, natural daylight, or a mixture of the two) of the same correlated colour temperature. Here, the reference is daylight of 6500 K (see Figure 1). (Note that the distortion graphics use different scales for different illuminations. In each, the border of the coloured circle represents the reference appearance.) Middle right panel: Photographs of an oil portrait (artist unknown) illuminated by M1, M2, and M3, respectively. Although colour appearance clearly changes, people tend to see the surfaces as the same under M1 and M2, but different under M3, at the cognitive level (far right panel). (TM-30-18 graphics produced with Luxpy [68]).

to examine whether color constancy mechanisms are specialised for particular surfaces and illuminations. In doing so, it will help to merge the two approaches: color science – to quantify the limits of appearance constancy, identifying conditions where sensory transforms are not enough, and vision science – to identify other factors which contribute to multi-level color constancy.

Is color constancy optimised for natural illuminations?

The observation that color constancy necessarily depends on the spectral properties of the illuminations and surfaces might be over 100 years old [28,29], yet the limits of color constancy have not been systematically explored in vision science. In constancy experiments, illuminations tend to be simulated daylights (23 of 39 studies reviewed in Ref. [10]). The advent of solid-state lighting [30] means that artificial illumination spectra are generally

more variable, more jagged, and less predictable than natural daylight (see example LED-based spectra M1 and M3 in Figure 2). Reported constancy levels (ranging from approximately 0.2–0.9, where 1 is perfect) might therefore be unrepresentative of the constancy achievable under contemporary artificial illuminations.

Traditional experimental paradigms for measuring color constancy, which typically involve assessing the appearance of individual surfaces in fixed scenes under a small number of distinct illuminations [10], tend not to address the hypothesis that color constancy might be optimised for natural illuminations under which the human visual system evolved [31]. Where they do, results disagree. Worthey [32] demonstrates, by reanalysing data from a now-classic asymmetric color matching experiment (comparing color appearance across different illuminations) [33] that constancy is better for ‘blue–yellow’ illumination shifts than ‘red–green’ shifts.

Table 1

Acronyms in color and vision science

CAM	Color appearance model	Converts tristimulus values into appearance descriptors (tristimulus values are directly derived from retinal receptor responses)
CAM02-UCS, CAM16-UCS	Types of uniform colour space (UCS)	Uniform color spaces – in which equal distances between color coordinates correspond to perceptually equal differences – based on different CAMs
CAT	Chromatic adaptation transform	Integral part of standard CAMs; depends on the adapting illumination; is applied to tristimulus values
CCI	Colour constancy index	Measure of colour constancy used in vision science, variously calculated, typically varying from 0 (no constancy) to 1 (perfect constancy)
CCT	Correlated colour temperature (of an illumination)	Colour temperature of point on the blackbody radiation curve closest to the chromaticity of the specified illumination (in a uniform color space)
CIE	Commission internationale de l'éclairage	International organisation that sets international standards for specifying light and color
CRI	Colour rendering index (of an illumination)	Describes the closeness of the color appearance of standard surfaces under the illumination to their appearance under a reference illumination (generally daylight of the same CCT). In the most recent CRMs, a single CRI is replaced by a suite of other descriptors
CRM	Colour rendering model (for illuminations)	Model for calculating CRIs and related descriptors of the effects of particular illumination spectra on color appearance of standard surfaces
D50, D65, D250, and so on.	Standard illuminants from the D series (CIE)	D illuminants represent average daylight of particular correlated colour temperatures. D50 (5000K), D65 (6500K), and so on.
IDT	Illumination discrimination task	Experimental paradigm for measuring sensitivity to illumination changes, through global scene appearance
TM-30-18	The most recent CRM defined by the Illumination Engineering Society	Provides multiple quantitative descriptors of the quality of a light source. Similar to other CRIs, these are based on comparison with color appearance as rendered by a reference illumination

Delahunt and Brainard [34], using an achromatic adjustment paradigm (measuring the chromaticity perceived as neutral, or achromatic) conclude that constancy is not better for daylight illuminations³.

More recently, using an asymmetric matching paradigm with real surfaces (Munsell chips) and illuminations (filtered tungsten lamps) Daugirdiene *et al.* [35] directly compared 4 illumination shifts away from a neutral reference, two paralleling and two orthogonal to the daylight locus (see Figure 1). The former gave higher mean constancy indices than the latter, with a distinct pattern of deviations. Further comparison between the two daylight-locus illuminations, using simulated scenes, gave higher color constancy for shifts toward an extreme blue (CCT >20 000 K) than yellow (2750 K) [36]. Conversely, using a similar set of four illuminations in simulated scenes, Wan and Shinomori [37] found the opposite: higher color constancy for illumination shifts away from neutral towards red and green than for shifts towards yellow and blue, with lowest constancy for the blue illumination shifts. The experimental paradigm was again asymmetric matching of individual surfaces, but under haploscopic viewing, with the two eyes separately

and simultaneously exposed to different illuminations. The difference in results might therefore be explained by the difference in adaptation state. Importantly, in both experiments, constancy indices vary significantly between surfaces, but with different patterns. Conflicts such as these drive home the need for paradigms that measure constancy globally rather than locally (as also urged by Ref. [10]), and which allow for full-field adaptation consistent with natural viewing conditions.

Where the aim is to examine contributory factors to color constancy it is generally not necessary to explore multiple types of illumination changes, but instead to vary the factors for a particular illumination change. For example, in examining the effects of surrounding spatial structure on constancy of real surfaces under real illuminations, Mizokami and Yaguchi [38] tested two illuminations only. They used a complex stimulus, with multiple illuminations at different depths, thereby challenging the single-source assumption on which sensory models such as the chromatic adaptation transform are based [2]. Under these conditions, constancy was weakened, and the contribution of structural coherency could be assessed. If color constancy were already at ceiling, the addition of another factor would not improve performance. It therefore makes sense to examine contributory factors to constancy for illumination changes under which color appearance is particularly unstable. Color science appearance and rendering models help to identify those conditions. Some factors might come into play only when

³ In achromatic adjustment, the appearance of a single surface only is measured: the mismatch between the chromaticity which the participant adjusts to be white (her perceptual whitepoint) and the chromaticity of the ambient illumination (the physical whitepoint) measures the deviation from perfect color constancy.

constancy is severely challenged; an example is the contribution of memory color for faces, revealed under extremely impoverished narrow-band illumination which effectively contracts the chromaticity gamut onto a single achromatic point. All surfaces lose color, and therefore all objects lose color constancy, apart from faces, which, paradoxically, appear greenish [39••].

The illumination discrimination task (IDT)

The need for a global measure of constancy that assesses appearance changes over an entire field and allows systematic exploration of the space of illuminations and surfaces [10] motivates new behavioural paradigms [40,41]. The global illumination discrimination task, or IDT [40], determines the perceptibility of illumination changes between two scenes. Complete imperceptibility of the illumination change would entail perfect stability of scene appearance, and therefore perfect color constancy (Table 1).

The IDT paradigm differs from typical asymmetric matching or achromatic adjustment in assessing thresholds for discriminating illumination changes via changes in surface appearance, rather than quantifying surface appearance itself under supra-threshold changes in illumination. It is related to earlier ‘operational constancy’ paradigms [42] and also parallels the development in color science of the TM-30 summary graphic for characterising the effects of the illumination on an expanded standard set of surface reflectances [7] (see Figure 2). The IDT paradigm was initially developed for immersive viewing of real surfaces illuminated by real light sources, using spectrally tuneable multi-channel LED luminaires, whose output light may be sculpted smoothly with almost infinite variety in real time. It therefore takes advantage of the possibilities offered by advances in lighting technology, and provides a ready way to assess their perceptual effects.

Results of the IDT suggest an evolutionary optimisation of the human visual system for natural illumination changes: illumination change discrimination thresholds vary significantly with direction [40,43,44], and in particular, tend to be largest in the bluish direction along the daylight locus, and smallest along the orthogonal reddish-greenish direction, starting from a neutral reference (see Figure 1).

Additional studies demonstrate that the extent of this optimisation depends on the scene surface composition. Using a similar illumination matching paradigm with simulated scenes, Lucassen *et al.* [41] found substantially higher constancy for supra-threshold blue and yellow illumination changes along the daylight locus than for orthogonal red or green changes. Yet the higher color fidelity for blue and yellow illuminations occurred only for natural images. For synthetic images with mean neutral chromaticities, fidelity ratings depended on the shape of the chromaticity distribution: higher fidelity occurred for illumination changes aligned with the major

axis of the distribution. The variation in fidelity with scene chromaticity statistics and illumination change direction was only partially explained by differences in average color appearance as predicted by CAMs. These results suggest that illumination changes in particular chromatic directions may be partially masked by scene surface chromaticity variations in those same directions.

Further exploration using the IDT in both real and simulated scenes [43,45•,46] shows that for chromatically biased scenes under neutral illumination, illumination changes in the opposite direction to the chromatic bias tend to be less discriminable than in other directions. For neutral (on average) scenes under chromatic illuminations, illumination discrimination thresholds tend to be largest in the direction away from the illumination chromaticity [45•]. In general, changes in illumination chromaticity towards neutral are hardest to discriminate. One interpretation of these results, in a Bayesian framework, is that the human visual system holds in memory a representation of the illumination, which decays toward a daylight prior over successive presentations of alternatives. The paradigm does not, though, presuppose that the human visual system must extract an estimate of the illumination spectral power distribution before recovering surface reflectance properties of objects. The IDT requires only that the participant determine whether the scene appearance has changed; thus, illumination discrimination may be high while illumination estimation remains poor. Whether scene appearance or illumination representations are held in memory during IDT trials remains an open question.

Is bluer better? The ‘blue bias’ in color constancy

The term ‘blue bias’ has been used for two distinct phenomena: (1) the reduced discriminability of blueish changes in illumination along the daylight locus ([40,45•,46]), relative to other directions, and (2) the tendency to perceive desaturated blues, or blueish whites, as white ([27,47]). The first phenomenon emerges in the IDT: over all reference illuminations and change directions, on average there is still a ‘blue bias’. Changes towards blueish daylight are the least discriminable [45•].

The second phenomenon arises continually in achromatic adjustment paradigms. The intra-individual and inter-individual variability in whitepoint settings tends to be greatest along a blue–yellow direction paralleling the daylight locus [48,49] (see Figure 1). Furthermore, for isolated surfaces presented under neutral illuminations, people on average tend to adjust their white points to be slightly blue, and to name desaturated blues as white but desaturated yellows as yellow [27]. Under more chromatic illuminations, for simulated [47] or real surfaces [50,51], people’s whitepoints generally show larger deviations from the illumination chromaticity the more distant it is from neutral, yet tend to deviate in the same direction,

towards the daylight locus [47,50]. Indeed, for simulated illuminations lying near or on the bluish daylight chromaticity of approximately CCT 8000 K, whitepoint settings show no deviation at all, almost perfectly matching the illumination chromaticity [47].

This 'blue bias' is taken to imply better color constancy for bluish changes in illumination along the daylight locus (also supported by other evidence [13]), whereas the blue bias in white perception is explained by a tendency to attribute bluish casts to the illumination rather than the material [26,27,47]. Both are consistent with the human visual system holding an inbuilt unconscious assumption that illuminations are more likely to be bluish, a plausible assumption given the skew in the distribution of natural daylight chromaticities towards blue. They are also consistent with the visual system having lower sensitivity to chromaticity changes over space or time which primarily cause increments in short-wavelength (S) cone activation, relative to S-cone decrements [52], although the tilting of the daylight locus relative to the S-cone-isolating axis in the chromaticity plane means that such low-level mechanisms cannot fully explain the asymmetry [27,53]. The underlying physiology also suggests that distinct S-cone pathways mediate spatial versus temporal contrast sensitivity, so the two effects might not be subserved by the same mechanism [54]. The argument that the visual system attributes bluish casts on surfaces to the illumination is also partly predicated on that notion that shadows tend to be bluish because directional lighting from the sun is yellower than diffuse lighting from the sky [55]. Yet this argument does not entail that bluish changes in illumination over time are more likely. It also implies that darker bluish casts should be more likely than brighter casts to be attributed to illumination effects (i.e. shadows), whereas naming results suggest the opposite: darker blues are more likely to be named blue than lighter blues [27].

To return to #thedress, it is plausible that because the neural mechanisms underlying color constancy are optimised for illuminations along the daylight locus, the spread of daylight chromaticities in the image increases the uncertainty over the particular illumination present, consistent with the masking effect in [41]. The 'blue bias' in both its forms also makes it more likely that the desaturated blue of the dress body is seen as a white surface under bluish daylight [27], explaining the 'white/gold' perception. 'Blue/black' is also plausible, given the likelihood of yellowish daylights. Yet, swapping the yellow and blue chromaticities while preserving their luminances, so that the dress body becomes light yellow and the lace dark blue, largely eliminates individual differences, almost all now agreeing that the body is yellow or gold [26,27]. Given the likeliness of dark blue shadows, this reversal is counterintuitive. It is possible that the prior likelihood for objects being bright and yellowish overrides the illumination prior. Again, it is clear that color constancy mechanisms depend on the

particular properties of surfaces and illumination spectra, even at levels beyond the chromatic adaptation transforms that limit appearance fidelity.

Object-metamerism and illumination-metamerism

A further challenge to color constancy that arises from contemporary advances in lighting is the increased likelihood of metamerism. The problem of object-metamerism is also not new in constancy studies (see Refs. [29,32,10]): the fact that two objects may appear identical (in terms of receptor responses to the reflected light) under one illumination, but different under another illumination, makes it theoretically impossible to achieve universal color constancy. Yet, prior knowledge of illumination and surface property likelihoods may enable higher-level constancy mechanisms to intervene; therefore, illumination changes which induce high degrees of object-metamerism are prime candidates for exploration of contributory factors to constancy beyond the appearance level.

The frequency of object-metamerism is relatively low for pairs of natural illuminations: Akbarinia and Gegenfurtner [56^{*}] estimate that only about 0.02% of surface pairs will be approximately metameric under the change from extreme blue (D250) to yellow (D40) daylight, from a collection of 11 302 natural and man-made surface reflectances. Yet, for any one indistinguishable pair of surfaces under D250, the likelihood that the pair become distinguishable under another may reach 60% [8^{**}]. The probability of metamerism increases with the chromaticity difference between natural illuminations [56^{*},57], and with the difference in smoothness of the respective spectra, with the largest frequencies of metamerism occurring for pairings of a narrow-band mixtures with any other illumination, reaching highs of about 0.06% metameric pairs [56^{*}]. Again, the occurrence of metamerism, as for color constancy, depends not only on the illumination but also on the surfaces: conditional probabilities of metamerism are higher for more variegated scenes [8^{**}], because the latter are more likely to contain highly chromatic surfaces.

The frequency of object-metamerism under contemporary illuminations is therefore likely to increase, compared to smoother traditional and natural illumination spectra.

A second challenge is illumination-metamerism. Two illuminations which differ in their spectra but appear the same when reflected from a physically white surface are metameric (see Figure 2). A chromatic surface will generally not appear the same under the two illuminations, and constancy mechanisms that rely solely on the chromaticity of the presumptive white surface in the scene – for example, chromatic adaptation transforms – will therefore fail to maintain color constancy for these surfaces. Thus, although the participant's perceptual whitepoint may indicate the level of chromatic adaptation [58,59], it cannot alone directly specify the color appearance of other surfaces in the scene,

and therefore cannot directly specify the extent of color constancy, particularly for contemporary illuminations which do not meet constraints on natural illuminations.

On the other hand, violating color constancy via metamer mismatching [60] may provide a means to distinguish between two objects of different surface reflectance. Successive illumination by irregularly changing spectra may reveal differences between objects which are otherwise camouflaged. Conversely, illumination spectra may be sculpted to enhance similarities between objects or to promote particular properties, opening up possibilities in artefact conservation and other domains [61].

Optimising the effects of artificial illumination

The dependence of color on the spectral properties of the illumination and surfaces, as well as on the individual viewer's visual system [44,62], therefore dictates greater attention to lighting design in settings where color appearance is critical to influencing behaviour, task performance, or aesthetic or emotional responses. Recent psychophysical studies suggest, for example, that in museum settings, viewers prefer 'cooler' illuminations for artworks than those traditionally used in museum settings [63]—indicating another form of 'blue bias'. Illumination preference clearly depends, though, on overall illuminance and the color rendering properties of the illumination [64,65]. Other results suggest that these preferences are at least partly mediated by the illumination effects on the chromatic gamuts of paintings [66]. Maximising the similarity of the chromatic gamut under the museum illumination to its original conception by the artist [67], created under the artist's working illumination, might be the optimal approach, highlighting again the usefulness and need of global measures of color constancy for particular scenes and surfaces. Thus, the challenges to color constancy posed by contemporary artificial illuminations may be eclipsed by the possibilities to optimise colors through tailoring illumination spectra to the behavioural needs of the individual.

Conflict of interest statement

Nothing declared.

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- of special interest
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